CENG 3420
Computer Organization & Design

Lecture 10: Performance

Bei Yu
CSE Department, CUHK
byu@cse.cuhk.edu.hk

(Textbook: Chapters 1.6 & 1.7)

Spring 2022

Throughput v.s. Response Time

Response time (execution time)

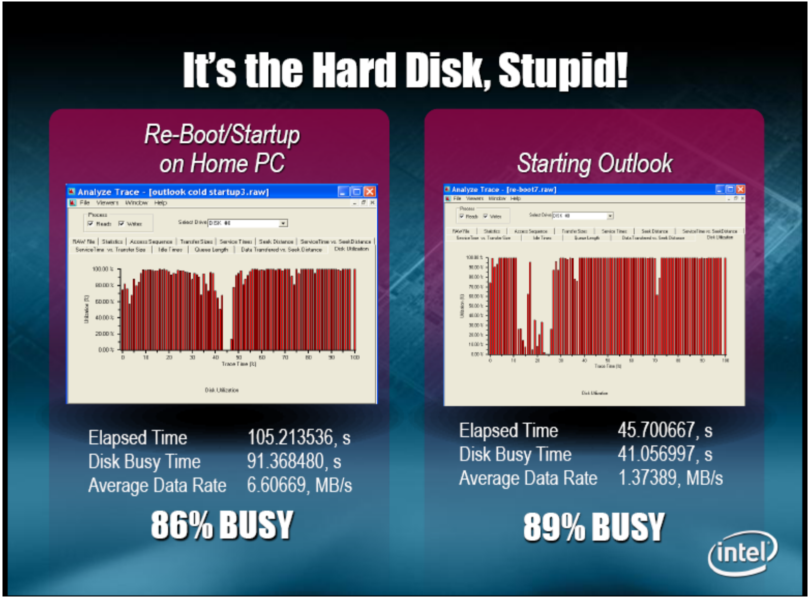
- The time between the start and the completion of a task.
- Important to individual users

Throughput (bandwidth)

- The total amount of work done in a given time
- Important to data center managers

Will need different performance metrics as well as a different set of applications to benchmark embedded and desktop computers, which are more focused on response time, versus servers, which are more focused on throughput

Response Time Matters



Justin Rattner's ISCA-08 Keynote (VP and CTO of Intel)

Defining (Speed) Performance

- To maximize performance, need to minimize execution time

$$\text{performance}_X = \frac{1}{\text{execution\_time}_X}$$

- If X is n times faster than Y, then

$$\frac{\text{performance}_X}{\text{performance}_Y} = \frac{\text{execution\_time}_Y}{\text{execution\_time}_X} = n$$

- Decreasing response time almost always improves throughput.

EX-1

If computer A runs a program in 10 seconds and computer B runs the same program in 15 seconds, how much faster is A than B?

Solution:

EX-1

If computer A runs a program in 10 seconds and computer B runs the same program in 15 seconds, how much faster is A than B?

Solution:

The performance ratio is $\frac{15}{10} = 1.5$, so A is 0.5 time faster than B.

Performance Factors

- CPU execution time (CPU time): time the CPU spends working on a task
- Does not include time waiting for I/O or running other programs

$$\begin{aligned}\text{CPU execution time} &= \#\,\text{CPU clock cycles} \times \text{clock cycle time}\\ &= \frac{\#\,\text{CPU clock cycles}}{\text{clock rate}}\end{aligned}$$

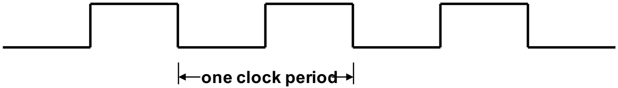
Can improve performance by reducing

- Length of the clock cycle
- Number of clock cycles required for a program

Review: Machine Clock Rate

Clock rate (clock cycles per second in MHz or GHz) is inverse of clock cycle time (clock period)

$$CC = \frac{1}{CR}$$



10 nsec clock cycle => 100 MHz clock rate

5 nsec clock cycle => 200 MHz clock rate

2 nsec clock cycle => 500 MHz clock rate

1 nsec (10^{-9}) clock cycle => 1 GHz (10^{9}) clock rate

500 psec clock cycle => 2 GHz clock rate

250 psec clock cycle => 4 GHz clock rate

200 psec clock cycle => 5 GHz clock rate

EX-2: Improving Performance Example

A program runs on computer A with a 2 GHz clock in 10 seconds. What clock rate must a computer B has to run this program in 6 seconds? Unfortunately, to accomplish this, computer B will require 1.2 times as many clock cycles as computer A to run the program.

Solution:

EX-2: Improving Performance Example

A program runs on computer A with a 2 GHz clock in 10 seconds. What clock rate must a computer B has to run this program in 6 seconds? Unfortunately, to accomplish this, computer B will require 1.2 times as many clock cycles as computer A to run the program.

Solution:

We denote x as clock cycle # on computer A, y as clock rate on computer B.

$$\begin{cases} x & = 10 \times 2 \times 10^9, \\ 1.2x & = 6 \times y. \end{cases}$$

$\rightarrow y = 4 \times 10^9 = 4$ GHz.

Clock Cycles per Instruction

- Not all instructions take the same amount of time to execute
- One way to think about execution time is that it equals the number of instructions executed multiplied by the average time per instruction

CPU clock cycles = # instruction $\times$ clock cycle per instruction

Clock cycles per instruction (CPI)

- The average number of clock cycles each instruction takes to execute
- A way to compare two different implementations of the same ISA

Effective (Average) CPI

$$\sum_{i=1}^{n} CPI_i \times IC_i$$

IC_i: percentage of the number of instructions of class i executed

CPI_i: (average) number of clock cycles per instruction for that instruction class

n: number of instruction classes

- Computing the overall effective CPI is done by looking at the different types of instructions and their individual cycle counts and averaging
- The overall effective CPI varies by instruction mix
- A measure of the dynamic frequency of instructions across one or many programs

Basic Performance Equation

$$\text{CPU time} = \text{Instruction count} \times \text{CPI} \times \text{clock cycle}$$

$$\text{CPU time} = \frac{\text{Instruction count} \times \text{CPI}}{\text{clock rate}}$$

Three key factors that affect performance

- Can measure the CPU execution time by running the program
- The clock rate is usually given
- Can measure overall instruction count by using profilers/ simulators without knowing all of the implementation details

CPI varies by instruction type and ISA implementation for which we must know the implementation details

EX-3: Using the Performance Equation

Computers A and B implement the same ISA. Computer A has a clock cycle time of 250 ps and an effective CPI of 2.0 for some program and computer B has a clock cycle time of 500 ps and an effective CPI of 1.2 for the same program. Which computer is faster and by how much?

Solution:

EX-3: Using the Performance Equation

Computers A and B implement the same ISA. Computer A has a clock cycle time of 250 ps and an effective CPI of 2.0 for some program and computer B has a clock cycle time of 500 ps and an effective CPI of 1.2 for the same program. Which computer is faster and by how much?

Solution: Assume each computer executes I instructions, so

$$\text{CPU time}_A = I \times 2.0 \times 250 = 500 \times I \text{ ps}$$
$$\text{CPU time}_B = I \times 1.2 \times 500 = 600 \times I \text{ ps}$$

A is faster by the ratio of execution times:

$$\frac{\text{performance}_A}{\text{performance}_B} = \frac{\text{execution\_time}_B}{\text{execution\_time}_A} = \frac{600 \times I}{500 \times I} = 1.2$$

Determinates of CPU Performance

$$\text{CPU time} = \text{Instruction count} \times \text{CPI} \times \text{clock cycle}$$

	Instruction_ count	CPI	clock_cycle
Algorithm			
Programming language			
Compiler			
ISA			
Core organization			
Technology			

Determinates of CPU Performance

$$\text{CPU time} = \text{Instruction count} \times \text{CPI} \times \text{clock cycle}$$

	Instruction_count	CPI	clock_cycle
Algorithm	X	X	
Programming language	X	X	
Compiler	X	X	
ISA	X	X	X
Core organization		X	X
Technology			X

EX-4

Op	Freq	CPI_i	Freq x CPI_i
ALU	50%	1	
Load	20%	5	
Store	10%	3	
Branch	20%	2	
			$\sum =$

1. How much faster would the machine be if a better data cache reduced the average load time to 2 cycles?
2. How does this compare with using branch prediction to shave a cycle off the branch time?
3. What if two ALU instructions could be executed at once?

Answer:

1. CPU time new = 1.6 x IC x CC so 2.2/1.6 means 37.5% faster
2. CPU time new = 2.0 x IC x CC so 2.2/2.0 means 10% faster
3. CPU time new = 1.95 x IC x CC so 2.2/1.95 means 12.8% faster

Benchmarks

A set of programs that form a "workload" specifically chosen to measure performance

- SPEC (System Performance Evaluation Cooperative) creates standard sets of benchmarks starting with SPEC89.
- The latest is SPEC CPU2006 which consists of 12 integer benchmarks (CINT2006) and 17 floating-point benchmarks (CFP2006).
- `www.spec.org`
- There are also benchmark collections for power workloads (SPECpower_ssj2008), for mail workloads (SPECmail2008), for multimedia workloads (mediabench) ...

SPEC CINT2006 on Barcelona ($CC = 0.4 \times 10^9$)

Name	ICx10^9	CPI	ExTime	RefTime	SPEC ratio
perl	2,1118	0.75	637	9,770	15.3
bzip2	2,389	0.85	817	9,650	11.8
gcc	1,050	1.72	724	8,050	11.1
mcf	336	10.00	1,345	9,120	6.8
go	1,658	1.09	721	10,490	14.6
hmmer	2,783	0.80	890	9,330	10.5
sjeng	2,176	0.96	837	12,100	14.5
libquantum	1,623	1.61	1,047	20,720	19.8
h264avc	3,102	0.80	993	22,130	22.3
omnetpp	587	2.94	690	6,250	9.1
astar	1,082	1.79	773	7,020	9.1
xalancbmk	1,058	2.70	1,143	6,900	6.0
Geometric Mean					11.7

How to summarize performance with a single number?

- First the execution times are normalized given the "SPEC ratio" (bigger is faster, i.e., SPEC ratio is the inverse of execution time)
- SPEC ratios are "averaged" using the geometric mean (GM)

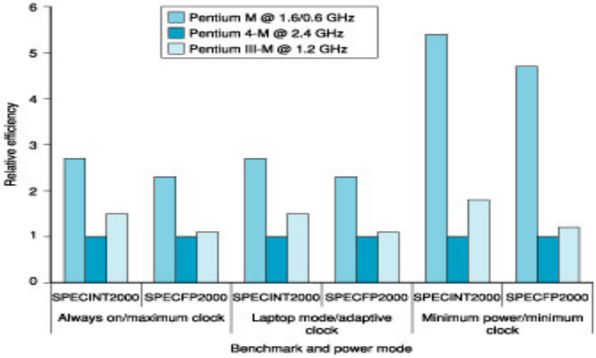
$$\mathrm{GM} = n \cdot \sqrt{\sum_{i=1}^{n} \text{SPEC ratio}_i}$$

Guiding principle – reproducibility

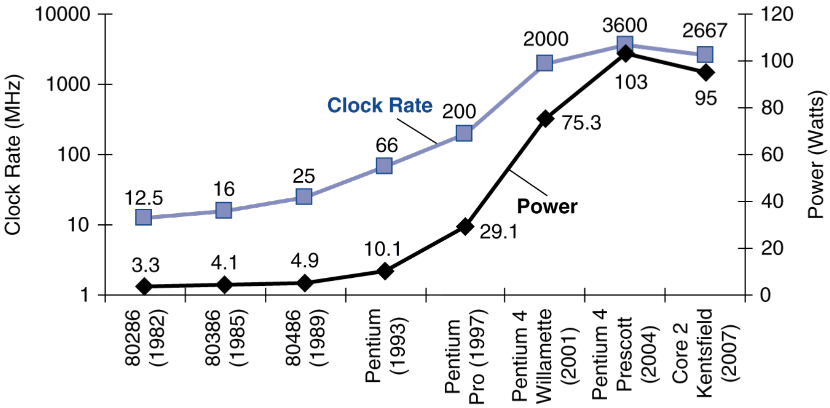
List everything another experimenter would need to duplicate the experiment: version of the operating system, compiler settings, input set used, specific computer configuration (clock rate, cache sizes and speed, memory size and speed, etc.)

Power Consumption

- Especially in the embedded market where battery life is important
- For power-limited applications, the most important metric is energy efficiency



Highest Clock Rate of Intel Processors



What if the exponential increase had kept up? Why not?

- Due to process improvements
- Deeper pipeline
- Circuit design techniques